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THE HIGH LIFT CHARACTERISTICS IN THE CASE OF THE V-WING CONCEPT

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THE HIGH LIFT BEHAVIOR OF A DIAMOND WING* /1***

H. Zimmer**

Theoretical experimental investigations of a new kind of diamond wing concept have been carried out at the Dornier Company since 1975. Experimental results are available for two models with two low speed channels and two high speed channels, and various parameters have been varied. The expected reduction of the induced and the wave resistance and an increase in the maximum lift have been confirmed by previous results. In addition, structural calculations for a hypothetical full scale version have been carried out. According to the stresses and deformations determined, the wing concept should also be able to control the loads.

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Short summary for information and documentation

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Abstract: (Technical-scientific and neutrally oriented short summary)

The new modern kind of diamond wing was investigated by Dornier both theoretically and experimentally since 1975. Experimental results of two models in two low speed channels and two high speed channels are variable, and various parameters have been varied. The expected reduction in the induced and the wave drag and an increase in the maximum lift have been confirmed by previous results. In addition, preliminary structural calculations with a hypothetical full scale version were carried out. According to the stresses and deformations found, the wing concept should be able to support the loads.

Key words (switch terms):
diamond wing, induced drag, wave drag, maneuver flaps, buffeting limits, side motion, polars, structural calculations.

1. INTRODUCTION /2

The aerodynamic requirements for aerial defense aircraft can be summarized in the following simplified way:

1. High maximum lift (short take-off and landing speed, short runways)
2. low drag for the subsonic speed range (maneuver flight)
3. low drag for supersonic speed (wave drag)
4. structure with the smallest possible weight (and cost) penalties.

When we consider these requirements in a design, the following problems occur: Requirements 1 and 2 can be satisfied, if one uses a wing with relatively high aspect ratio or span. In order to satisfy requirement 4, relatively thick wing profiles are required in order to provide the largest possible spar height. However, this contradicts requirement 3, because in a supersonic flow, the thinnest possible profiles should be used , because the wave drag increases about according to the square of the profile thickness. On the other hand, the high load multiples which occur require relatively compact wings because of requirement 4 (small aspect ratio), which in turn contradicts requirements 1 and 2.

In order to make improvements here, additional vortices were produced by means of wing leading edges installed ahead of the body (Strakes, F-16, F-17), or an auxiliary wing is used in the canard configuration (Viggen, Kfir). Various investigatons are known where these additional vortices are stabilized by means of gas jets.

Movable leading edge and/or trailing edge flaps in various /3 designs are widely used.

The requirements mentioned above are very contradictory and, of course, are most easy to satisfy by means of a movable wing, which in slow flight represents a wing with a high aspect ratio and for supersonic speed, it comes very close to the most favorable delta wing with a small aspect ratio. The exceptional aerodynamic performance of such a wing, however, is counter-balanced by an exceptional amount of complexity (costs) and increased weight. Many aircraft designs with movable wings developed up to the present (Figure 1) show that some designers are prepared to pay this large price for aircraft with special missions (low altitude flight).

There are investigations of achieving a better compromise between the high speed and the low speed requirements using simple means. Recently, an investigation has become known [7] (see Figure 2) which again uses a wing strut, which many designers have tried to remove from the wing since the beginning of aviation. In this application, and because of the strut, maximum wing thickness was reduced from 4.5 to 3.1%, which resulted in a reduction in a total drag of the aircraft of about 8% at Mach = 1.6. A wing support and the thereby reduced wing volume was also considered during the development of the diamond wing. However, in addition, the advantages of dynamic interferences will be exploited.

2. FUNDAMENTALS OF THE DIAMOND WING CONCEPT /4

A wing moving through the air at the speed U with lift experiences friction drag and induced drag. The creation of this drag can be explained by means of a momentum analysis as follows: the lift produced by the wing is the reaction of the momentum of the air reached by the wing and moved downstream. The energy contained in a mass flow moving downwards represents the induced drag multiplied by the speed. According to this analysis, the planar ellipse wing only reaches the air mass which is inside a tube with a diameter of the wing span around the wing.

The basic knowledge about the induced drag comes from the beginning of aviation research (for example, [1], [2]) and particularly the fact that by using nonplanar wing configurations, one can bring about a reduced induced drag, as would be possible using a plane elliptical wing. The most important results are summarized in Figure 3 ([2], [3], [4]). The positive effect of these wing systems can be explained as follows: Because of their extension in the z-direction, they reach a larger air mass than a flat wing. This ratio of the induced drags (Figure 3), therefore, can be interpreted as well as the reciprocal value of the ratio of the covered mass flows. For example, a box wing with a high ratio of 0.5 will cover twice the air mass of a flat elliptical wing.

These results have been known for a long time and have again become important because of the requirement to reduce the drag of aircraft, for example, by modifying the wing tips (for example, [3], [4], [5]).

Figure 3 gives a frontal view of wing systems, but from the structural point of view they do not promise any special advantages. It seems that the diamond shaped wing in the frontal view is better suited for this, because the wings support one another mutually. The relative induced drag of such a configuration is shown in Figure 4 (recalculation according to [6]). /5

Its effectiveness is considerably better than the configuration of Figure 3, but for a completely designed wing we are less interested in the relative induced drag than in the induced drag directly. Various wing systems can be compared with the same aerodynamic performance (same induced drag for same width). For a given factor of the relative induced drag, the span has to be recalculated accordingly. Figure 5 shows a comparison of 3 wings and the optimum multiwing (the box wing) with a 60% of relative induced drag, the diamond multiwing with 95.4% and the flat elliptical wing. Even though the diamond multi-wing has a span which is about 20% greater than the box wing, it has a lower washed surface than the box wing, which is expressed here in the developed wing s.

In previous analyses ([1], [2], [3], [6]) only the shape of the cross section through the wing wake far behind the wing entered in the calculations but not the position of the individual elements of the wing system in the x-direction. A two-dimensional multi-element profile theory shows that this displacement as well as the profile shape is very important, because the mutual influencing has an effect on the boundary layer development on the individual elements. Already in the early phases of aircraft development, a configuration was found [8], where the various aerodynamic effects [9] were combined in a favorable way. This so-called optimum biplane has a more favorable polar than the equivalent single wing and a higher maximum lift, as Figure 6 shows. /6

These characteristics together with the fact that by means of the mutual wing support for a given aspect ratio results in a lower wing volume than for a single wing, led to the definition of a wind tunnel model [10] shown in Figure 7. This was designed as a variation model, so that it could be investigated with various wings and control surface positions. The upper wing and lower wing were equipped with curvature flaps at the trailing edges. The diamond wing and the comparison wing were untwisted and had symmetric profiles. After the conclusion of the main part of the measurements the model was slightly modified (Figure 7).

3. RESULTS OF THE INVESTIGATIONS /7

Theoretical and experimental investigations were carried out in subsonic and supersonic flows. Experimental results are available for two models in two low speed and two high speed channels, and various parameters were varied. Several results on the aerodynamic behavior of the base configuration with the influence of flaps will be given in the investigated angle of attack and Mach number range.

3.1 LOW SPEED RANGE

First, we made comparisons between experiments and theoretical analyses of the wings in the low speed range. Figure 8 gives the discretization of the wings in the form of a vortex network for calculating, using the vortex lattice method. A nonlinear wake was used [11]. The figure shows a comparison between the calculated lift and drag (wing alone, without strake) and the measurements (entire configuration with control surface). The increase in lift of the diamond wing is somewhat larger than that of the individual wing, as is the maximum lift. The theoretical induced drag is about 12% less for the diamond wing. In the measurements we only reached the expected difference at angles of attack above 12°.

The effect of flaps at 25% chord was also investigated. The theoretical influx on the lift and on the pitch moment is given in Figure 9 for the flap deflection possibilities. It is found that the lower flap alone is about three times as effective as the top flap, as far as the additional lift is concerned (downwind influence). Both flaps together have an effect which is slightly higher than that of a flap on a single wing. As the variations of the pitching moment show, the upper flap brings about a positive zero moment. The moment of the diamond wing with complete flap deflection is less by exactly this amount than that of the single wing.

The structural investigations show that a common outer wing has /8
a favorable effect on the deformation of the wing complex under the aerodynamic load. This modification was, therefore, investigated on a priority basis. Figure 10 shows the theoretical flap effectiveness according to Figure 9. In principle, nothing changes from the results with the outer wing.

For comparison purposes, Figure 11 shows the flap effectiveness from low speed measurements (without elevation control surface). The expected tendency of the flap effect on lift does not occur. Also the pitch moment varies as expected according to the calculation. For small lift coefficients and for the selected moment reference point $(\frac{1}{4}\ l\mu)$ the wing-body combination alone is already stable. The stability decreases at high angles of attack because of separation in the outer regions of the wing (only without horizontal tail assembly). The upper flap brings about a positive additional moment of the expected magnitude. The diamond wing is a configuration with which a positive zero moment of the wing-body combination can be reached without a negative effect on lift. The flight mechanical possibilities from this are discussed in [12]. In the case of a single wing, the production of a positive zero moment by S-struts, flap deflection upwards, twisting is always related to a loss in lift. In addition, Figure 11 shows the influence of the flaps on the polar.

At DFVLR, in depth investigations of the measured diamond wing-horizontal tail assembly combination were carried out. Among other things, they made a theoretical analysis of the flap influence for vortex layers which roll up in the wake. Figure 12 shows a result from [13]. This gives the discretization of the configuration made up of vortex networks and the rolling up of the vortex layer with pylon and outer wings. The lower wing flap is deflected.

The wing flaps were also measured when deflected to one side, in order to determine their roll effect (flaperon). The roll effectiveness of the lower flap is substantially greater than the upper flap because the downwind influence has the same effect as in the case of an additional lift, and the span is also larger. /9

Figure 13 at the top also shows how the flaps could be used to control drag. By deflections in opposite directions, lift changes can be equalized.

By an appropriate combination of the flap deflection on one wing side and by using the vertical tail assembly, a side force of sufficient size could be produced without additional control surfaces. (For example, pylon flaps). This is shown in the center of Figure 13. The side force exerted by the vertical tail assembly is supported by pressure forces which apply to the side wall of the body because of the flap deflection. These were effective over the measured angle of attack Mach number range (bottom Figure 13). This sideways motion was also investigated in the entire speed range. In the low speed range, measurements were performed up to large angles of attack. Figure 14 shows the most important static sideways motion derivatives.

It is found that the side slip rolling moment remains stable over the angles of attack range of the diamond ring. However, it becomes unstable at 16° for a single wing (Figure 14, center). The wind flag stability decreases less steeply for a diamond wing than for a single wing, and is maintained up to a large angle of attack (Figure 14, bottom).

The behavior of a diamond wing was investigated as well up to large angles of attack. Figure 15 shows the lift coefficient up to angle of attack of 60°. We find a continuous variation over the maximum lift, which itself is very flat. Figure 16 shows the corresponding pitch moment and the polars. Here again we showed continuous variations without special features up to angles of attack of 60°.

The behavior of a diamond wing for large angles of attack is uncritical overall, because the flow remains attached up to large angles of attack and separates only gradually because of the advantageous gap configuration. /10

3.2 HIGH SPEED RANGE

We will now give several results from the high speed range investigations. The effectiveness of wing flaps (maneuver flaps) was investigated over the entire Mach number range. It makes sense to use them up to about M = 0.95. Above this, the clear configuration is more favorable. Figure 17 shows the variations of buffet-onset in the high subsonic range and in the transonic range were the most important measured configurations. The criterion for defying this limit was twice the base value of the square of the average of the signal of the roll moment balance. Here we see an advantage of the diamond wing configuration. The buffet limits are lifted somewhat because of the flaps.

These variations only give the beginning of rocking motion. Of course, one will attempt to even go beyond this boundary as much as possible without endangering the structure of the aircraft. As the example of a transonic polar shows (M = 0.9) in figure 17, the polar of a diamond wing is clearly favorable in the light buffet range than is the single wing.

Figure 18 shows how the lift varies with the Mach number over the range. The lift increase of the configurations of interest here as a function of Mach number is given and the measured lift curves for 3 Mach numbers. These results show that in a supersonic flow the lift increase of a diamond wing is smaller than that of a single wing. The linearized supersonic profile theory also gave such a result as indicated in Figure 16. This can be attributed to the /11 interference effect of two wings which are parallel (without overlap).

When considering the drag, we first considered the supersonic form drag, that is the wave drag for zero lift. Figure 19 shows a comparison of the theoretical wave drag according to [14] (supersonic area rule) of a model configuration and measurements. The peak in the calculated curve, where the wing always had a supersonic leading edge, is washed out in the measurements. Figure 20 shows the variation of the measured wave drag values of the model with diamonds and this is compared with single wings. The expected reduction has, therefore, been demonstrated.

We will now discuss two examples about the variation of the supersonic total drag with increasing lift. Figure 21 on top shows the polars of diamond wings and single wings at Ma = 1.46. For small lift coefficients, the total drag is reduced by about 15% by means of the diamond wing. As the lift increases the difference becomes smaller until the polars intercept. A two-dimensional analysis using linearized supersonic profile theory with a Mach number reduction caused by the influence of sweep also shows this tendency (parallel profiles). This can be seen from the two-dimensional polars on Figure 21. The interference effect of the two polars results in an improvement of the polar below a certain lift coefficient. Above this there is a deterioration compared with a single profile. However, the lift coefficients which occur for supersonic flight are small, so that the advantage can be exploited. Figure 20 shows the results for M = 2. The Mach number of the two-dimensional polar corresponds to the normal component perpendicular to the wing leading edge (Figure 20 below). The measurement trends of Figure 22 top here again correspond to those of the previous two-dimensional theory. The lift coefficient flow which occur at this Mach number also here lie in the region of positive interference between about 10 up to the limiting case of zero lift of 20% of the total drag reduction brought about by the diamond wing.

3.3 STRUCTURAL CALCULATIONS /12

In such a nonconventional wing configuration, the structural feasibility also is very important. We will briefly discuss this problem. For the most possible realistic structural configuration, we specified a hypothetical full-scaled version from various comparable project studies. These are shown in Figure 23. The calculated flight weight was 7500 kg. The wing configuration as well as the distribution of the relative thickness (referred to each wing chord) are given in Figure 24. In absolute terms, the wing is very thin and is about 1.5% of the total wing chord at the thinnest point. The idealization of the wing complex for structural calculations is shown in Figure 25, according to [10]. The calculation shows that for a 12 g fracture load, the skin of the wings could not be figured in 5 mm anywhere, because an Al structure is assumed. The twist of the unit at fracture load is less than 3°. The very thin wings are, therefore, possible with this stiff design. If we allow larger relative thicknesses, the skin thickness could be thinner accordingly.

4. NOTATION /13

b	wing span
C_a	profile lift coefficient
C_A	total lift coefficient
C_{A_B}	lift coefficient for buffet onset

C_{L_β}	side slip rolling moment derivative
C_M	pitch moment coefficient
C_{N_β}	side slip yaw moment derivative
C_W	drag coefficient
C_{W_i}	coefficient of induced drag
$C_{W_{i_{ell}}}$	coefficient of induced drag of the flat elliptical wing
ΔC_{W_o}	wave drag resistance coefficient
C_y	side force coefficient
C_{y_β}	side force derivative
d	profile thickness
h	height of wing system
HLW	vertical tail assembly
l	profile chord
l_μ	aerodynamic reference wing chord
M, Ma	Mach number
Re	Reynolds number
RMS_L	quadratic square of the pitch moment signal of the strain gauge value (Root mean square)
S	developed arc length
SLW	vertical tail assembly
W_i	induced drag /14
$W_{i_{ell}}$	induced drag of elliptical wing
X, Y, Z,	rectangular coordinate system
α	angle of attack
β	side slip angle
ε_H	horizontal tail assembly trim angle
θ	wing V-position
η	dimensionless span
η_K	flap deflection angle
$\eta_{O,U}$	deflection angle of the top and lower flaps
κ	ratio of the induced drag to that of the flat elliptical wing
λ	wing aspect ratio

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